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LETTER TO THE EDITOR

Comparison of observed with model hadron charge ratio of secondary cosmic rays

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Abstract. The validity of previous comparisons between model results and observations of the neutral to charged ratio of hadrons in the atmosphere is re-examined. We then select the most appropriate published data plus data taken by the authors at Chacaltaya and compare them with model results.

The principal tool for abstracting information on high-energy interactions ($E > 10^3$ GeV) from cosmic-ray observations is compared with results of modelling calculations for the propagation of hadrons in the atmosphere. Pertinent to the present rate are the modelling results of Pal and Peters (1964), Frazer *et al* (1972), Garraffo *et al* (1973) and Adair (1974). At the energies and altitudes in question, the hadrons will be accompanied by an electromagnetic air-shower component of more than several hundred particles on average. But, in many experiments, the trigger condition or data selection has incorporated a bias against local particle densities above some value ρ_m. Unless ρ_m is greater than several particles/m^2, the bias can severely limit the usefulness of comparison of the data with modelling results. We believe that this point has received insufficient attention in the past. In this Letter, we shall try to clarify the situation by utilizing only the results of observations where the anti-shower requirement is stated and is least restrictive. In addition, our own observations at Chacaltaya will be briefly described and the results included in the comparison with models.

Our measurements of the neutral to charged hadron ratio were made at Mt Chacaltaya, Bolivia, at 5200 m (530 g cm^{-2}). The primary instrument was a 60 in multi-plate cloud chamber, which was situated at the centre of the BASJE scintillator array (Suga *et al* 1962). Hadrons were identified by their nuclear interactions in the cloud-chamber plates and their energies were determined from the number of particles in the shielded BASJE scintillators below the cloud chamber. The effective lower energy limit was $\sim$100 GeV and the weighted average energy was 240 GeV.

Our trigger permitted a maximum local particle density of $\rho_1 \leqslant 6{\cdot}5$ particles/m^2 at N_1, the BASJE scintillator directly above the cloud chamber.

The cloud-chamber photographs were used to select 865 hadron interactions that met our geometry and quality requirements. The observed neutral to charged ratio of these hadrons, n/c, was $0{\cdot}62 \pm 0{\cdot}03$, where the error is statistical. Two corrections

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are required to convert to *n/c* of the *incident* hadrons. These corrections result from the fact that the charged component has a significant admixture of pions (Brooke *et al* 1964, Alakoz *et al* 1968, Cowan and Matthews 1971, additional results of this experiment to be published). The pions have a smaller inelastic cross section than nucleons (e.g. Whitmore 1974) and hence the detection efficiency is smaller for pions. On the other hand, pions pass more freely through the material above the observation region of the cloud chamber. The net effect is zero within a few per cent for this experiment.

We now come to the main points of this Letter—the selection of experimental results that are most suitable for comparison with existing modelling results, and conclusions derived from the comparison. Because of the technical problem of sorting particles out of showers, no hadron measurement has been made without some local particle-density bias.

Hadrons are always detected by their nuclear interaction in a target, characterized by one particle above and many particles below the target. If the trigger required only the particles below the target it would mainly function on air showers. This is usually avoided by requiring a low particle density above the target and a high one below. If the low-density requirement is too stringent, the results of the experiment can no longer be usefully compared with the available models. We have therefore selected only three experiments: Alakoz *et al* (1968) permitted $\rho \leqslant 10\ \mathrm{m}^{-2}$, Cowan and Matthews' (1971) sample 'included associated incoming particles with small separation', and the present results permitted $\rho \leqslant 6{\cdot}5\ \mathrm{m}^{-2}$. The three results for *n/c* are shown in figure 1. The discussion will be based on *n/c*, since this is the quantity that is most directly deduced from observation.

In other measurements (Lal *et al* 1963, Brooke *et al* 1964, Jones *et al* 1971, Aguirre 1972), there were strong anti-shower requirements. In still others (Grigorov *et al* 1965, Abdullaev *et al* 1971), published information was insufficient for evaluation of shower bias.

The first detailed modelling for the development of the hadron component in the atmosphere (Pal and Peters 1964) gave *n/c* as a function of atmospheric depth. Their results (see figure 1) are of less interest than later work, which utilizes recent accelerator data. The only recent modelling that leads to *n/c* is that of Garraffo *et al* (1973) who give the neutron to proton ratio (n/p) and the pion to proton ratio (π/p). From these ratios, we have deduced the *n/c* curves for 100 GeV and 200 GeV shown in figure 1. (It should be noted that the comparison of modelling results with observed n/p made by Garraffo *et al* (1973) in their figure 1 is not informative for two reasons: the experimental results are for *n/c*, and each result has a strong or an unknown anti-shower bias.) The most recent modelling (Adair 1974) utilizes the state of the art accelerator data and hadron interaction models.

Adair calculates n/p at 600 to 800 g cm^{-2} atmospheric depth (figure 1). When one estimates *n/c* for Adair's model by using π/p of Garraffo *et al* (1973) to convert Adair's n/p to *n/c*, the result is $n/c \simeq 0{\cdot}24$, shown in figure 1.

We are now in a position to make the most significant comparison of model results with observation that is possible using currently available information. This is done in figure 1, where we see that the model values for *n/c* are (*a*) too low, particularly at high altitude, and (*b*) too flat in their altitude dependence.

(*a*) Adair (1974) has addressed this question, but he made his comparison with observations that were not pertinent. However, our comparison leads to the same result. Therefore, Adair's conclusions are pertinent, namely that the deuteron

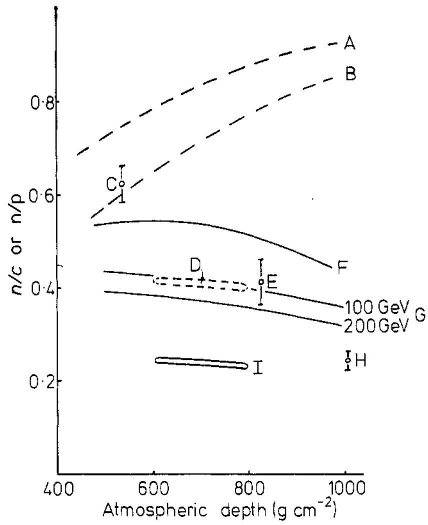

Figure 1. The ratios n/p (neutrons to protons) and *n/c* (neutral to charged hadrons) against atmospheric depth. A, n/p (Pal and Peters 1964); B, n/p (Garraffo *et al* 1973); C, *n/c* (University of Michigan results, this paper); D, n/p (Adair 1974); E, *n/c* (Alakoz *et al* 1968); F, *n/c* (Pal and Peters 1964); G, *n/c* (Garraffo *et al* 1973); H, *n/c* (Cowan and Matthews 1971); I, *n/c* (Adair 1974, Garaffo *et al* 1973).

component of the primaries is greater than he assumed (thus enhancing the neutron component) and/or charge exchange is 'extensive' at ~1000 GeV. The former is not borne out by subsequent data (Teegarden *et al* 1975), which give a relative intensity of primary deuterons no higher than 15% of the alpha particle intensity. Thus, the conclusion is that charge exchange is extensive at cosmic-ray energies, as it is at accelerator energies, which now extend up to a few hundred GeV (Bubble Chamber Group, University of Michigan).

(*b*) The too-flat altitude dependence of the *n/c* results of models indicates that (i) the calculated n/p rises too rapidly with depth and/or (ii) the calculated π/p rises too slowly with depth. Our conclusion from (*a*) above makes (i) unlikely. Thus we are led to (ii), which is probably due to both the interaction path of 110 g cm^{-2} for pions used by Garraffo *et al* (1972) being too short, and also the assumed pion inelasticity of one being too large. At accelerator energies up to a few hundred GeV there is evidence for both the former, since the ratio of pp to π^-p inelastic cross sections is ~1·5 (Whitmore 1974), and also the latter, since an energetic leading π^- is observed in ~25% of the π^-p inelastic interactions (Diamond and Erwin 1975, Kenney 1975, private communication).

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